Complex Networks

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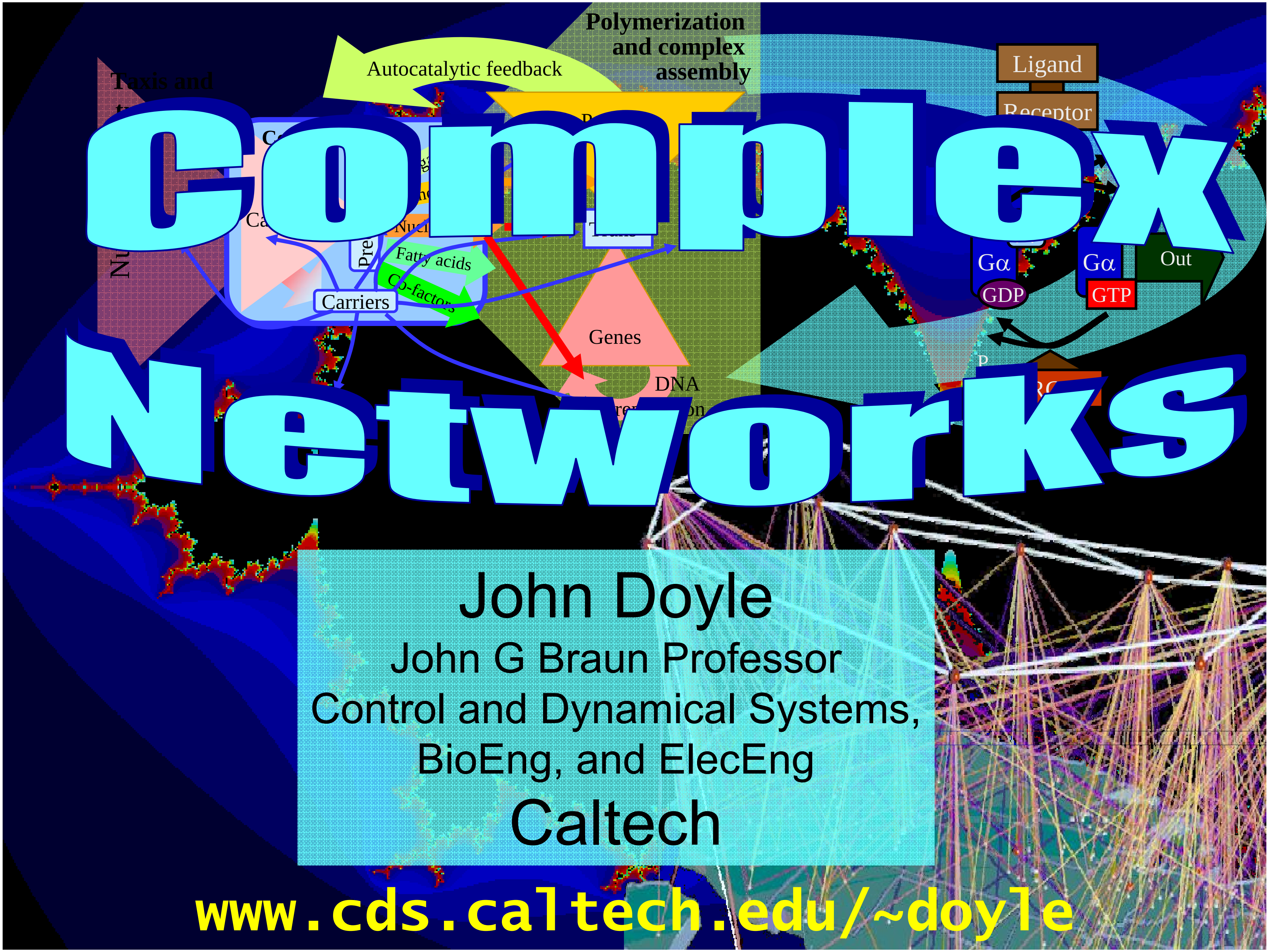

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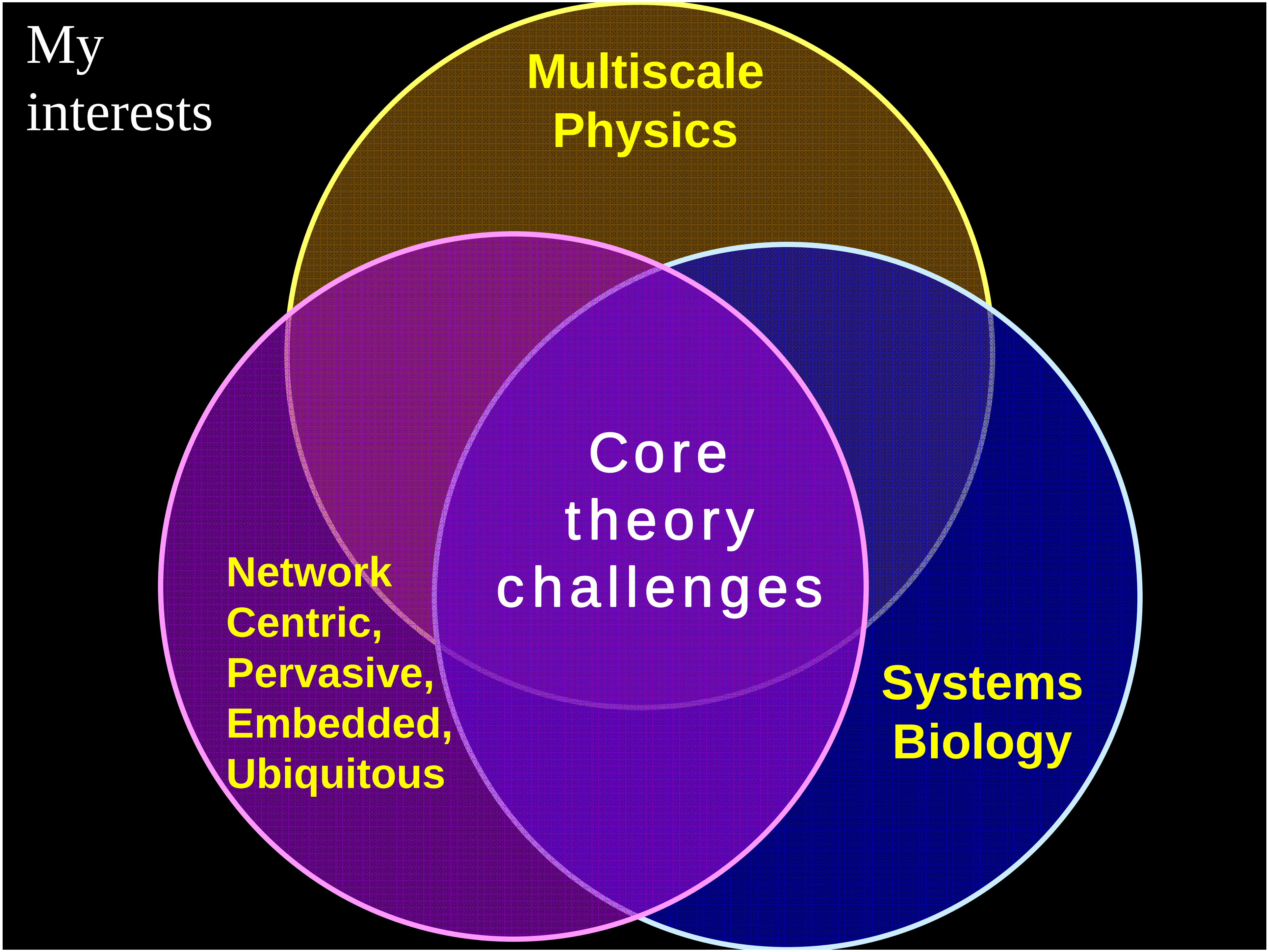
My
interests
Multiscale
Physics
Core
theory
challenges
Network
Centric,
Pervasive,
Embedded,
Ubiquitous
Systems
Biology

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- Lee Center for Advanced Networking (Caltech)

Challenges in the NS report:

1. *Dynamics, spatial location, and information propagation in networks.*
2. *Modeling and analysis of very large networks.*
3. *Design and synthesis of networks.*
4. *Increasing the level of rigor and mathematical structure.*
5. *Abstracting common concepts across fields.*
6. *Better experiments and measurements of network structure.*
7. *Robustness and security of networks.*

What is “network science”?

- What is ***science***? (A greatly oversimplified view.)
- Tentatively consider these subdomains:
  - Physics
  - Biology
  - Social Sciences
  - Math
  - Technology

- These have enormous methodological differences that have grown with time

What is “network science”?

- (Also an oversimplified but hopefully useful taxonomy)
- Already exist distinct subdomains:
  - Network Technology (NetTech)
  - Network Biology (NetBio)
  - Network Social Sciences (NetSoc)
  - Network Math (NetMath)
  - Network Physics (NetPhys)
- These have ***even greater*** methodological differences than their traditional antecedents
- Spectacular but very uneven progress

The good news: Net Tech

- Network technology (interpreted broadly) has been wildly successful…
- … yielding a "networked planet" for energy, food, information, goods and materials,…

- "Network centric technology" has also made it possible to build and ***demo*** almost anything we can envision.

- Thus…

Hard, but demonstrated capability

1. ***Dynamics, spatial location, and information propagation in networks.***
2. ***Modeling and analysis of very large networks.***
3. ***Design and synthesis of networks.***
4. *Increasing the level of rigor and mathematical*
5.
6. *rk*

- Needs focus and funding
- But engineers have demonstrated they can solve such problems
- ***If*** properly motivated. (Big IF.)

7. *Robustness and security of networks.*

The structure of scientific explanation

Observe: Observe and formulate research plan

Data: Gather and analyze data

Simulate: Model and simulate

Proof: Prove conjectures

- Different branches of science use these unevenly and in very different ways.
- “Network science” is currently even more extreme.
- Network science will demand a fundamental rethinking of their roles, particularly ***proof***.
- “Tower of Babel” must be avoided.

Tower of Babel?

1. *Dynamics, spatial location, and information propagation in networks.*
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The Net “Tower of Babel”

NetTech: global infrastructure, Internet, wireless, energy, transportation, supply chain…, silicon, fiber, …, network centric, ubiquitous, embedded-everywhere, nano-,…

NetBio: systems biology, genomics, *omics, evo-devo, bioinformatics, …, metabolic, transcriptional, signal transduction, regulatory,…, medicine, epidemiology, emerging infections, medical disaster management, integrative physiology, ecology, …

NetPhys: multiscale, turbulence, chaos, stat mech,…, fractals, criticality, self-similarity, scale-free, cellular automata, universality, edge-of-chaos, renormalization,…

NetSoc: economics, sociology, psychology, politics, management, law, ecology… , scaling, small worlds…

NetMath: graph, information, control, dynamical systems, complexity, formal methods, optimization,…

Hard but clearly doable

1. *Dynamics, spatial location, and information*

- Needs focus and funding
- Requires engagement of ***all*** subfields
- Can be done
- ***If*** properly motivated.

5. *Abstracting common concepts across fields.*
6. *Better experiments and measurements of network structure.*
7. *Robustness and security of networks.*

The dominant challenge

1. *Dynamics, spatial location, and information propagation in networks.*
2. *Modeling and analysis of very large networks.*
3. *Design and synthesis of networks.*
4. *Increasing the level of rigor and mathematical structure.*
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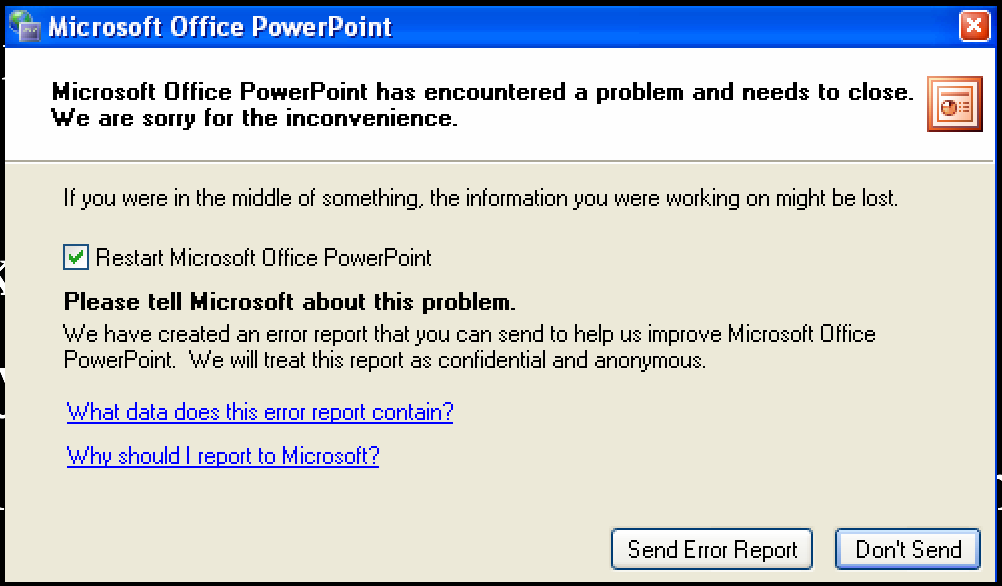
The bad news

- Network technology has been ***too*** successful…
- … yielding a "networked planet" for good ***and bad***…
- … including all manner of catastrophe and destruction.

- "Network centric technologies"
  - Largely deliver what we design them to do.
  - But fail because they create new problems we ***did not expect.***

The bad news

- Network technology has been ***too*** successful…
- … yielding a “networked planet” for good ***and bad***…
- … includ destruction.



- “Network
  - Largel do.
  - But fai ms we ***did not expect.***

Robust yet fragile

- "Network centric technologies"
  - Create extraordinary capabilities and ***robustness***
  - And unexpected new ***fragilities***

- Science deals poorly or not at all with this challenge.
- "Network science" must do better.

The dominant challenge

1. *Dynamics, spatial location, and information propagation in networks.*
2. *Modeling ... ge networks.*
3. *Design a ...*
4. *Increasi ... nathematical structure ...*
5. *Abstracti ... oss fields.*
6. *Better experimen ... asurements of network structure.*
7. ***Robustness and security of networks.***

We could try our best and still fail on this challenge, which would be catastrophic.

Nightmare?

Biology: We might accumulate more complete parts lists but never “understand” how it all works.

Technology: We might build increasingly complex and incomprehensible systems which will eventually fail completely yet cryptically.

Nothing in the orthodox views of complexity says this won’t happen (apparently).

HOPE?

Interesting systems are **robust yet fragile**.

Identify the fragility, evaluate and protect it.

The rest (robust) is **“easy”.**

Nothing in the orthodox views of complexity says this can’t happen (apparently).

Reason for ***cautious*** optimism

1. *Dynamics, spatial location, and information propagation in networks.*
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3. *Design and synthesis of networks.*
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Human complexity

Robust	Yet Fragile
☺ Efficient, flexible metabolism	☹ Obesity and diabetes
☺ Complex development	☹ Rich parasite ecosystem
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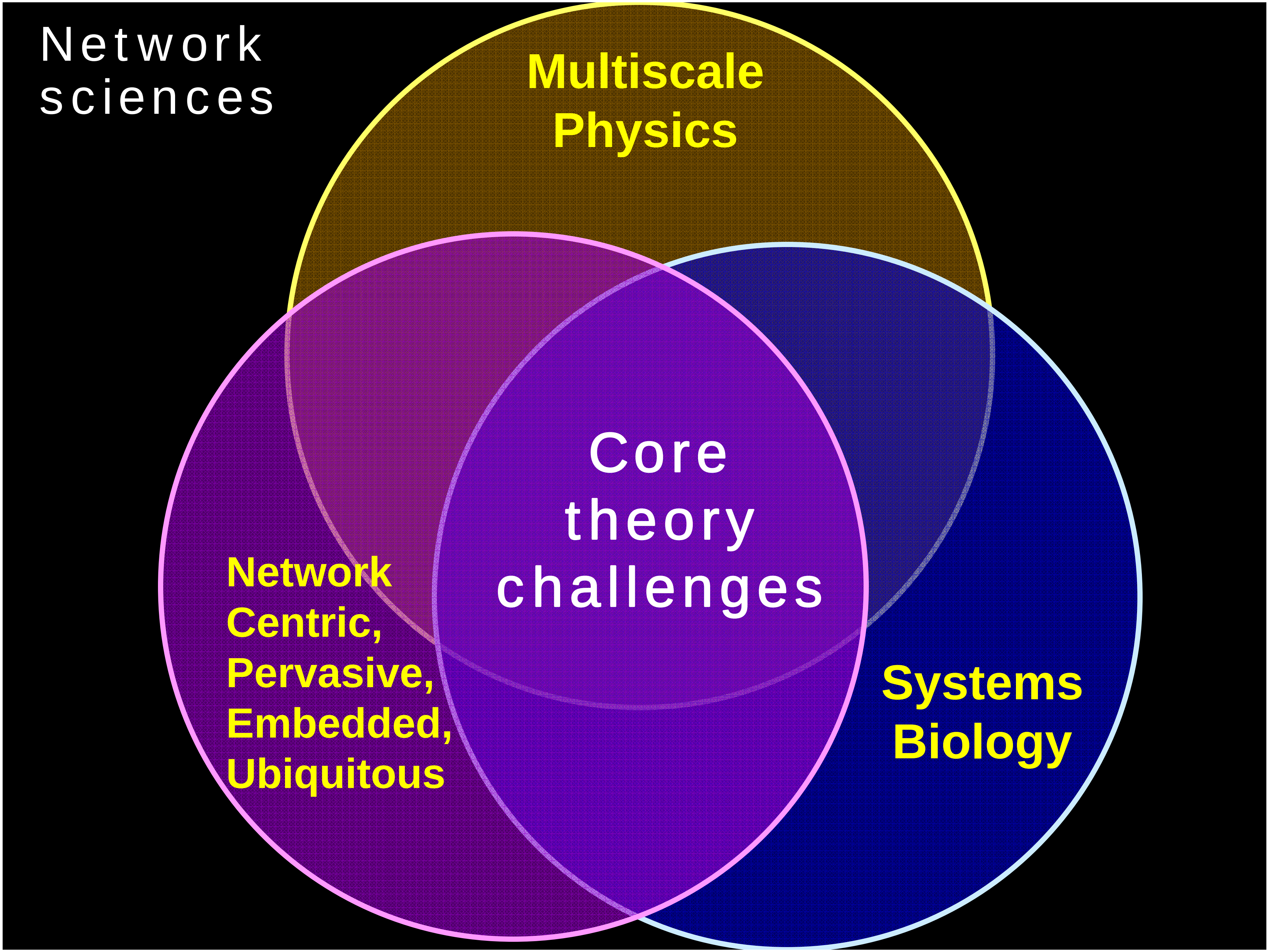
Complex societies	☠ Epidemics, war, …
Advanced technologies	Catastrophic failures

- Evolved mechanisms for robustness *allow for*, even *facilitate*, novel, severe fragilities elsewhere (often involving hijacking/exploiting the same mechanism)
- Universal challenge: Understand/manage/overcome this robustness/complexity/fragility spiral


Network sciences
Multiscale Physics
Core theory challenges
Network Centric, Pervasive, Embedded, Ubiquitous
Systems Biology

Status

Consistent, coherent, convergent understanding.

Remarkably common core theoretical challenges.

Yet also striking increase in unnecessary confusion???

Core theory challenges

Pervasive, Networked, Embedded

Dramatic recent progress in laying the foundation.

Core theory challenges

Systems Biology

Common themes

- Organizational principles/structures
- Robust yet fragile (RYF)

Examples: All of advanced technologies, all of biology

Robust Yet Fragile (RYF) = Demos great, works most of the time, occasionally fails ***catastrophically***

(HOT)

Core theory challenges

Pervasive, Networked, Embedded

Core theory challenges

Systems Biology

Theoretical foundations for networks

- The most rigorous, sophisticated, and applicable of existing theories
  - Computation
  - Control
  - Communications
- Have become fragmented and isolated
- Failed attempts at unified "new ***sciences***"
- Need new ***mathematics***
- Recent progress has been spectacular, both in rigor and relevance

A look back and forward

- The Internet architecture was designed w/o a "theory"
- Many academic theorists said it would never work
- Recent "emergent" theories are wildly wrong (there have always been specious claims of "Achilles heels")
- We now have a nascent and relevant theory that confirms that the engineers were right (Kelly, Low, Vinnicombe, Paganini, Papachristodoulou, Li, Alderson,Willinger,…)

- A strikingly parallel (but less complete) story exists in biology
- For future networks and technologies, "systems of systems," systems biology of the cell, organism and brain, etc, let's hope we can avoid a repeat of this history. (Looks like we have a good start…)

Background progress: Biology

- With molecular biology’s detailed description of components
- And growing attention to systems biology (e.g. see Stelling, Covert, Haddad, etc)
- The organizational principles of biological networks are becoming increasingly apparent
- We are beginning to see the principles of architecture as well as components and circuits

- Unfortunately, we are also seeing substantial errors and resulting confusion in the analysis of the structure of large networks.
- These errors should be straightforward to correct but have so far been remarkably resistant.

Background progress: Technology

- Advanced technology's complexity is now approaching biology's.
- While the components differ, there is striking convergence at the network level of architecture and the role of layering, protocols, and feedback control in structuring complex multiscale modularity.
- For example, new theories of the Internet and related networking technologies have led to test and deployment of new protocols for high performance networking.

- The same analysis errors crept in here but have largely been eliminated.

Background progress: Mathematics

- New mathematical frameworks suggests that this apparent network-level evolutionary convergence within/between biology/technology is not accidental
- But follows necessarily from universal requirements to be
  - efficient,
  - adaptive,
  - evolvable,
  - robust to perturbations in their environment and component parts

Background progress: Mathematics

- This mathematics blends (from engineering) theories from
  - optimization,
  - control,
  - information, and
  - computational complexity
- with diverse elements in areas of mathematics (e.g. operator theory and algebraic geometry) not traditionally thought of as applied.

Background progress: Lessons learned

- Foundational issues this progress suggests
- Describe with minimal mathematics and minimal domain-specific expertise
- (My prejudices: It must ultimately lead to a mathematical foundation, but it can't start only there.)
- Learn from success stories in a broad sense, and contrast them with failures

- Good news: Much of the existing confusion can be cleared up with even minimal rigor in treating math and data

Complex Networks

- Widely agreed that “complexity” and “networks” are important scientific and technological challenges
- Little broad agreement on even the most basic notions…
- Substantial (and unnecessary) “confusion” about even the most basic, fundamental, and foundational results (Tower of Babel)
- Need a simpler, more coherent, and more ***rigorous*** taxonomy/ontology (The Tower is not unavoidable)

- And ultimately a more unified, integrated, fundamental conceptual/theoretical (i.e. ***mathematical***) foundation?

Confusion about basics

Questions and issues:

- The essence of “complexity”?
- The foundational challenges and issues?
- The sources of so much (unnecessary) confusion?
- Existing success stories?
- Differences from the failures?
- Encouraging new research?

Defining “complexity”: outline

- Aim: simple but universal taxonomy
- Widely divergent starting points from math, biology, technology, physics, etc,
- Can be organized into a coherent and consistent picture

1. Review “simplicity” in scientific exploration
2. How simplicity breaks down and why
3. Distinguish “emergence” from “organization”
4. Universal challenges
5. Dramatic success stories
6. Promising initial results

	Small models	Large models
Robust/ Short proofs	Simplicity	Organization
Fragile/ Long proofs	Emergence	Irreducibility

Where we're going

Three key dimensions to complexity will be explored

- ***Small/large*** descriptions, models, and theorem statements
- ***Robust/fragile*** features of a system in response to perturbations in components or the environment.
- ***Short/long*** lengths of proof of properties, including generating (counter)-examples by simulation (Deeply intertwined with ***robust/fragile*** dimension.)

	Small models	Large models
Robust/ Short proofs	Simplicity	Organization
Fragile/ Long proofs	Emergence	Irreducibility

Where we're going

- Three key dimensions to complexity will be explored
- Four distinct kinds of complexity can be described across these three dimensions.
- Robustness/fragility and short/long are deeply connected and their dimensions "collapse"

- Much confusion comes from viewing this too narrowly

	Small models	Large models
Robust/ Short proofs	Simplicity	
Fragile/ Long proofs		

The nature of simplicity

Simple questions:
- Small models
- Elegant theorems
- Elegant experiments

Simple answers:
- Simple outcomes
- Robust, predictable
- Short proofs

Reductionist science: Reduce the ***apparent complexity*** of the world to an underlying simplicity.

Physics has for centuries epitomized the success of this approach.

The basis of rigor

Simple questions:

- Simple models
- Elegant theorems
- Elegant experiments

Simple answers:

- Simple outcomes
- Robust, predictable
- Short proofs

• Mathematical rigor is based on theorems and proofs without experiments

• Physics “rigor” is based on elegant experiments with simple outcomes and no need for theorems, proofs, or statistics

• Complex systems research must ***expand*** on these sources of rigor, not retreat from rigor as an objective

• What are challenges extending rigor to complexity?

The basis of rigor

- Complex systems create unique challenges for both theoretical and experimental rigor, (particularly with regard to architecture):
  - Scalability to large systems
  - Robustness to component/environment uncertainty
  - Evolvability to unanticipated long-term changes
- Must explicitly mix theory, simulation, including hardware and human in the loop, and experiments in new and novel ways
- Huge issue needing careful thought, not enough said here (sorry)

	Small models	Large models
Robust/ Short proofs	Simplicity	
Fragile/ Long proofs	Emergence	

1930s: The end of certainty

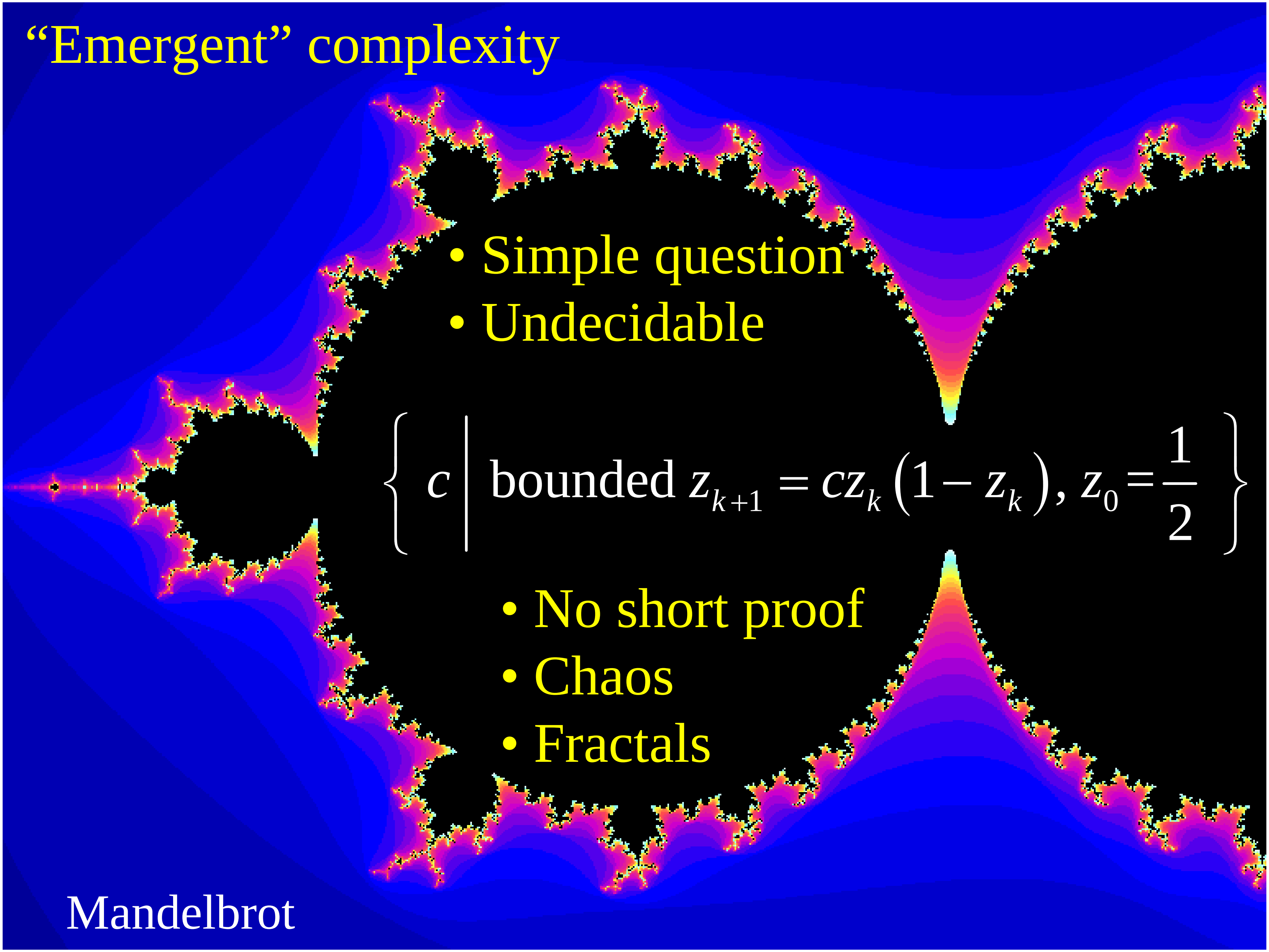
Simple questions:

- Small models
- Elegant theorems
- Elegant experiments

Simple answers:

- ~~Simple outcomes~~
- ~~Robust, predictable~~
- ~~Short proofs~~

- Godel: Incompleteness, Turing: Undecidability
- Even simple questions can be “complex” and fragile
- Profoundly effected mathematics and computation
- Modest impact on science, primarily through emphasis on “emergent complexity”



“Emergent” complexity

• Simple question

• Undecidable

$$\left\{ c \,\middle|\, \text{bounded } z_{k+1} = c z_k \left(1 - z_k\right),\ z_0 = \frac{1}{2} \right\}$$

• No short proof

• Chaos

• Fractals

Mandelbrot

1960s-Present: "Emergent complexity"

Simple questions:

- Small models
- Elegant theorems
- Elegant experiments

Dominates scientific thinking today

Complexity:

- "New sciences"
- Unpredictability
- Chaos, fractals
- Critical phase transitions
- Self-similarity
- Universality
- Pattern formation
- Edge-of-chaos
- Order for free
- Self-organized criticality
- Scale-free networks

Unfortunately, has become a source of systematic errors.

	Small
Robust/short	Simplicity
Fragile/long	Emergence

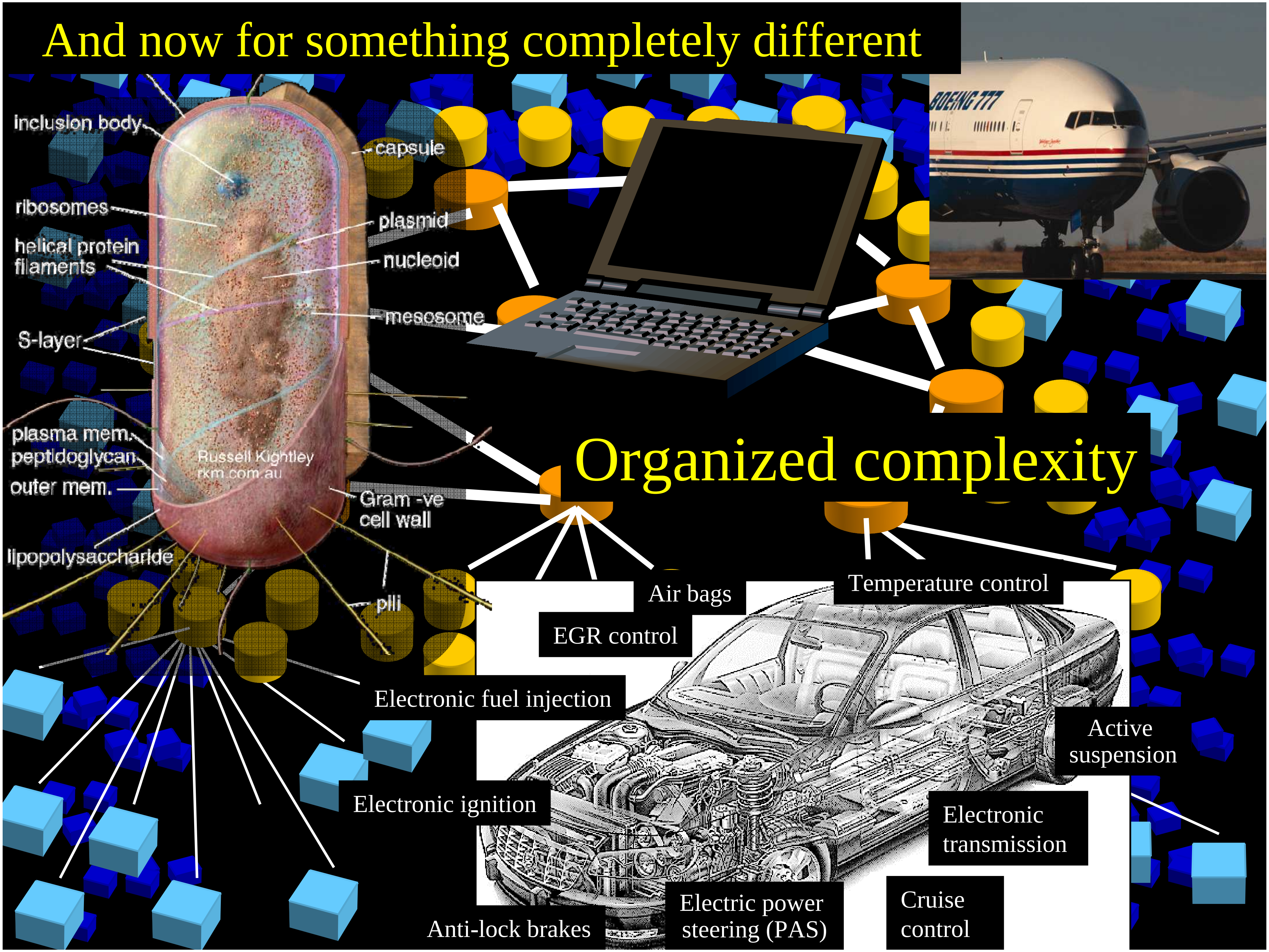
To make a long story short…

- ***Small*** applies to the description of experiments, theorems, models, systems
- ***Robust/short*** means experiments and real systems have easily predictable behaviors, and mathematical theorems have easy, short proofs or counterexamples.
- ***Fragile/long*** means unpredictable results, difficult to study, long proofs, and large changes in outputs due to small changes in inputs or models
- "Emergence" means that ***small*** (in all senses) can nevertheless lead to ***fragile/long*** (also in all senses).

Emergent complexity

- The most fragile details of complex systems will likely always be experimentally and computationally intractable.
- Fortunately, we care more about understanding, avoiding, and managing fragility (than about all its details)

	Small models	Large models
Robust/ Short proofs	Simplicity	Organization
Fragile/ Long proofs	Emergence	


And now for something completely different
inclusion body
capsule
ribosomes
plasmid
helical protein filaments
nucleoid
mesosome
S-layer
plasma mem.
peptidoglycan
outer mem.
Russell Kightley
rkm.com.au
Gram -ve cell wall
lipopolysaccharide
pili
BOEING 777
Organized complexity
Air bags
Temperature control
EGR control
Electronic fuel injection
Active suspension
Electronic ignition
Electronic transmission
Cruise control
Electric power steering (PAS)
Anti-lock brakes

1900s: The triumph (and horror) of organization

~~Simple questions:~~

- ~~Small models~~
- ~~Elegant theorems~~
- ~~Elegant experiments~~

Simple answers:

- Simple outcomes
- Robust, predictable
- Short proofs

- Complex, uncertain, hostile environments
- Unreliable, uncertain, changing components
- Limited testing and experimentation

- Yet predictable, robust, reliable, adaptable, evolvable systems

Organized complexity

- Requires highly organized interactions, by design or evolution
- Completely different theory and technology from emergence

Simple answers:

- Simple outcomes
- Robust, predictable
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- Complex, uncertain, hostile environments
- Unreliable, uncertain, changing components
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Organized complexity

- Neither reductionist science, nor (more significantly) “emergent” complexity theory is much help with organized complexity (and often just leads to further obfuscation).
- This no longer should be a controversial statement, given recent history, but it still is
- Organized complexity has a long history, but has exploded in importance in the last few decades with network technology and biology
- What are the keys to understanding organized complexity?

A look back and forward

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- Many academic theorists said it would never work
- Recent "emergent" theories are wildly wrong (there have always been specious claims of "Achilles heels")
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	Small	Large
Robust	Simplicity	Organization
Fragile	Emergence	

Math, bio, & tech

- ***Small*** and ***Large*** apply to the description of experiments, theorems, models, systems
- Bio and tech systems have enormously long and complex descriptions, yet extraordinarily robust behaviors
- Indeed, robustness drives their complexity, and more fragile systems could be much simpler
- Much of the apparent complexity of modern mathematics is to create a robust and rigorous proof infrastructure

	Small	Large
Robust	Simplicity	Organization
Fragile	Emergence	

Robust
yet
fragile

- Even systems most designed/evolved for extreme robustness, also have fragilities and this is ***not accidental***
- The most designed/evolved systems have systematic, universal spirals of robustness/complexity/fragility
- Understanding/controlling this “spiral” is arguably the central challenge in organized complexity
- There are hard constraints on robustness/fragility (from theory not widely known outside engineering)
- Thus robustness is never “free” and is paid for with fragility somewhere

	Small	Large
Robust	Simplicity	Organization
Fragile	Emergence	

Issues

- Emergence and Organization are opposites, but can be viewed in this unified framework
  - Emergence celebrates fragility
  - Organization seeks to manage robustness/fragility
- Much confusion is caused by failure to “get this”

- The most fundamental challenge of organizing complexity for robust and evolvable systems is inherent and unavoidable robustness/fragility tradeoffs

Human complexity

Robust	Yet Fragile
☺ Efficient, flexible metabolism	☹ Obesity and diabetes
☺ Complex development	☹ Rich parasite ecosystem
☺ Immune systems	☹ Inflammation, Auto-Im.
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Complex societies	☠ Epidemics, war, …
Advanced technologies	Catastrophic failures

- Evolved mechanisms for robustness *allow for*, even *facilitate*, novel, severe fragilities elsewhere (often involving hijacking/exploiting the same mechanism)
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Human complexity and RYF

Robust	Yet Fragile
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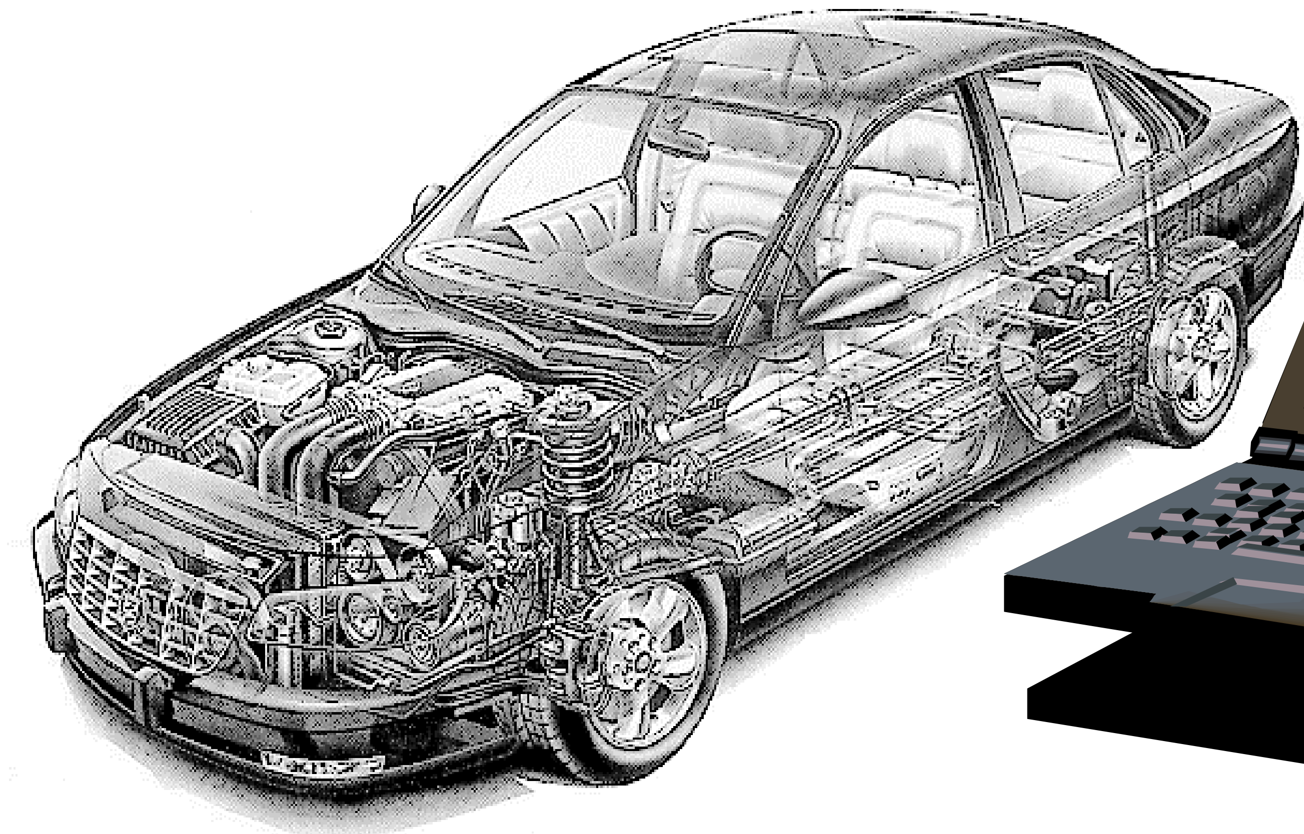
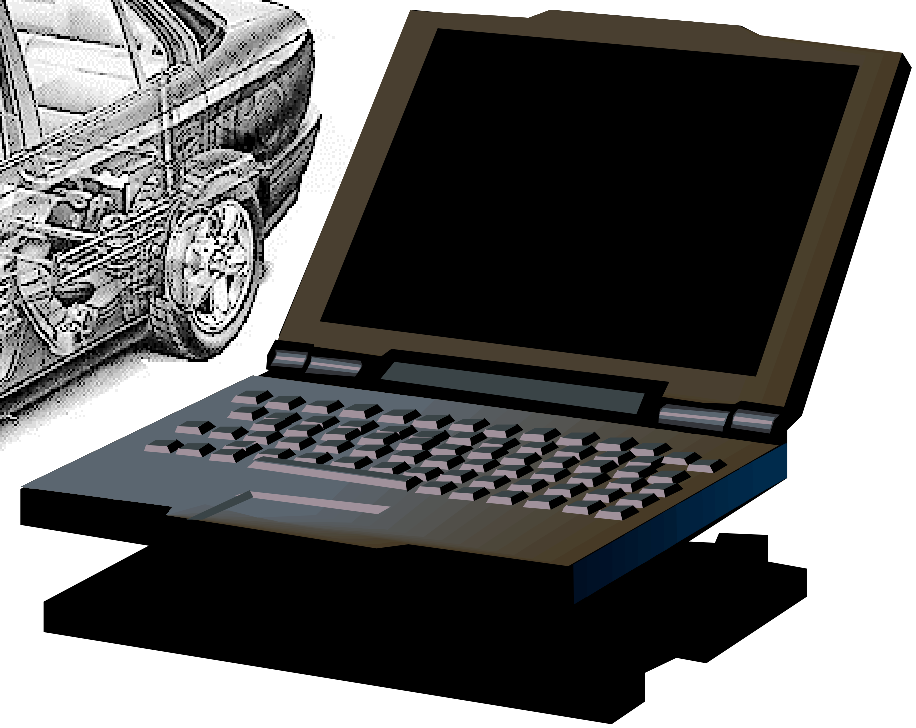
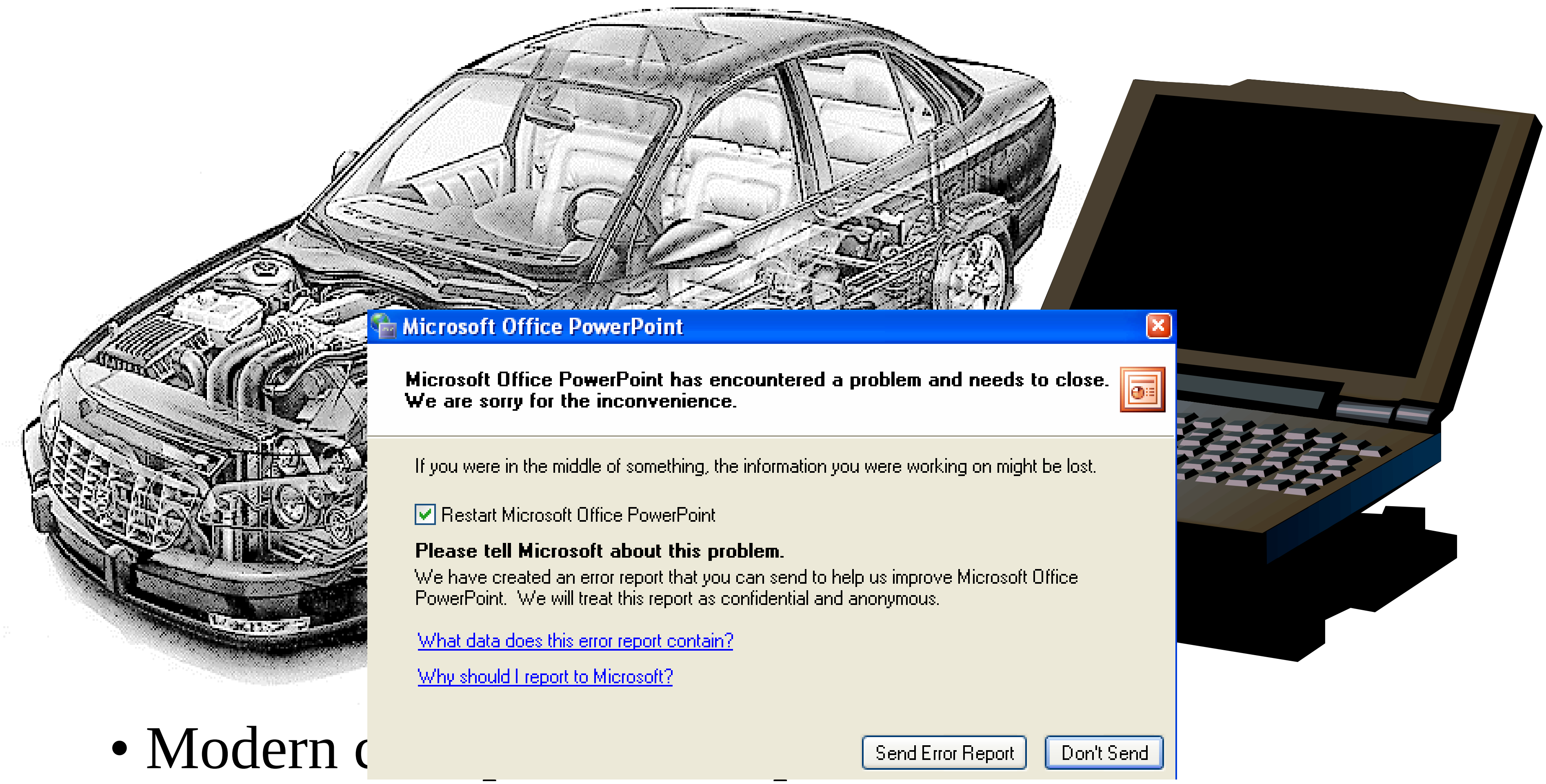
- Inflammation: classic example of RYF
  - Normally robust and invisible
  - Complexity becomes apparent due to fragilities

• Modern cars, planes, computers, etc have exploding internal complexity
• They are simpler to use and more robust.
• They tend to work perfectly or not at all.



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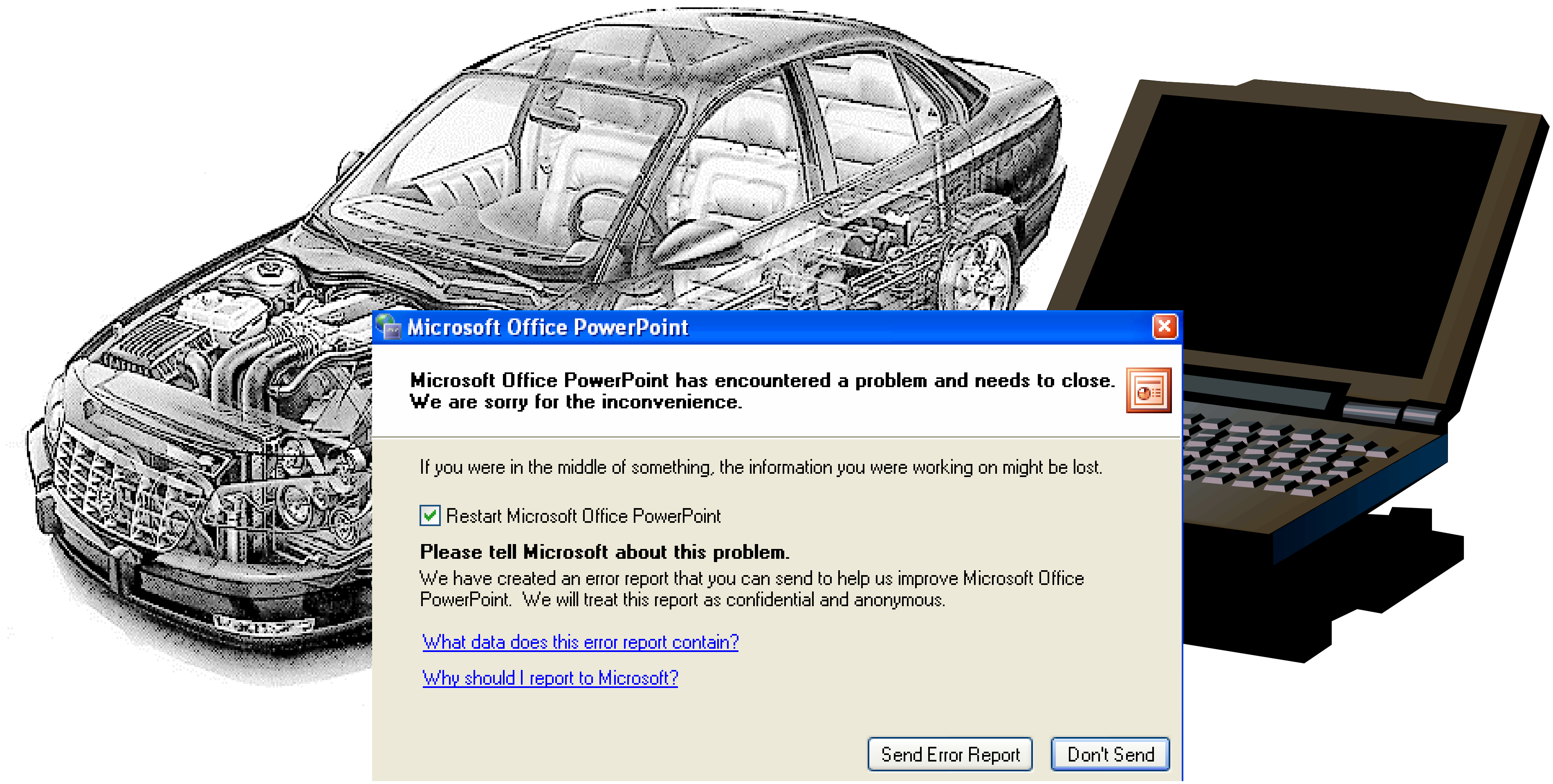


Robust yet Fragile

Nightmare?

Biology: We might accumulate more complete parts lists but never “understand” how it all works.

Technology: We might build increasingly complex and incomprehensible systems which will eventually fail completely yet cryptically.

Nothing in the orthodox views of complexity says this won’t happen (apparently).

HOPE?

Interesting complex systems are **robust yet fragile**.

Identify the fragility, evaluate and protect it.

The rest (robust) is **"easy".**

Nothing in the orthodox views of complexity says this can't happen (apparently).

	Small	Large
Robust	Simplicity	Organization
Fragile	Emergence	Irreducibility

The full picture

- Some fragilities are inevitable in robust complex systems.
- But are there circumstances in which large descriptions, long proofs, and high fragility are ***desirable***?

- Yes, all are important features of cryptography and security, including host-pathogen interactions.
- So organized complexity is not merely about robustness but about the ***management*** of ***functional*** robustness and fragility ("emergence" is avoided as much as possible)
- Emergence focuses on pure surprise and fragility

	Small	Large
Robust/short	Simplicity	Organization
Fragile/long	Emergence	Irreducibility

Recap

Three key dimensions to complexity

- ***Small/large*** descriptions, models, and theorem statements
- ***Robust/fragile*** features of a system/model in response to perturbations in components or the environment
- ***Short/long*** lengths of proof of properties, including generating (counter)-examples by simulation (deeply intertwined with ***robust/fragile***)

- Much existing confusion is created by failure to grasp these distinctions (and lack of standard terminology).

Nightmare

	Small	Large
Robust/short	Simplicity	Organization
Fragile/long	Emergence	Irreducibility

Recap

• The nightmare is that technology, biology, and medicine (and social sciences) get stuck with only spiraling complexity, large models/descriptions, no coherent understanding, and uncontrollable fragilities.

• The hope is that more rigorous methods can provide systematic tools for managing complexity and robustness/fragility.

• There is both tremendous progress and substantial confusion, and robustness/fragility is at the heart of both.

Errors and confusion

	Small	Large
Robust/Short	Simplicity	Organization
Fragile/Long	Emergence	Irreducibility

Emergence & “New Sciences” of Complexity, Nets, etc…

- Confusion about origin and nature of chaos, power laws, phase transitions, fractals, simulation, etc
- Lack of minimal mathematical and statistical rigor
- Misapplication to the organized complexity of biology, ecology, technology (and social systems?)
- Classic (high-impact) errors in ecosystems, wildfires, Internet topology, bio networks, physiology, etc
- Fortunately, minimal impact in medicine/technology

Errors and confusion

	Small	Large
Robust/Short	Simplicity	Organization
Fragile/Long	Emergence	Irreducibility

Organization & the arrogance of technology

- Underestimating the impact and consequences of fragilities created by complexity
- Failure to manage complexity/robustness/fragility spiral
- Classic (high-impact) consequences in global warming, antibiotic resistance, software failures, spam and viruses, terrorism (see also “war against”), etc…

Errors and confusion

	Small	Large
Robust/Short	Simplicity	Organization
Fragile/Long	Emergence	Irreducibility

Organization and the source of complexity

- Complexity in bio and tech networks is driven by control systems (where/when/how), not part count (who/what).
- Bio: Protein-coding gene count weakly correlated with apparent organized complexity of organism
- Tech: Explosion in complexity in computer networks, autos, planes, devices, supply chains, package delivery, etc is in ***where/when/how*** more than ***who/what***.

Errors and confusion

	Small	Large
Robust/Short	Simplicity	Organization
Fragile/Long	Emergence	Irreducibility

Irreducible complexity, intelligent design, and creationism

- Overly mystical (like Emergence) and underestimates the organized complexity of evolved organisms
- *If* biology were irreducibly complex, it would
  - require a (rather incompetent) creator, since it would be too fragile to evolve
  - also be so fragile as to require ***constant intervention*** of supernatural control mechanisms

	Small	Large
Robust	Simplicity	Organization
Fragile	Emergence	

High variability?

- Emergence and Organization both involve high variability, but with opposite mechanisms
  - Emergence as the result of bifurcations to chaos, and phase transitions and criticality
  - Organization as the result of high performance robust control systems
- Additional confusion is caused by failure to "get this" distinction
- May be very important in acute illness

Organization of emergent mechanisms?

Can be exploited,
But in a managed way

Complexity:

- “New sciences”
- Unpredictability
- Chaos, fractals
- Critical phase transitions
- Self-similarity
- Universality
- Pattern formation
- Edge-of-chaos
- Order for free
- Self-organized criticality
- Scale-free networks

	Sma
Robust	
Fragile	Eme

Robust/fragile describes system ***behavior*** in response to ***perturbations*** in components or environment.

- Systems can be robust for some features/perturbations yet fragile in others
- Organized complexity involves systematic management of robustness/fragility through design or evolution
- There are hard constraints on robustness/fragility (not to be widely known outside of engineering systems)
- Theories on hard limits must be driven by
  - –Limits on component technology
  - –System-level requirements
  - –Uncertainty in environment

Hard limits and tradeoffs: Status

On systems and their components

- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing/Gödel)

- Essential in existing treatments of complexity
- Fragmented, incompatible, incomplete
- Need more integrated view and have beginnings
- All have “robust yet fragile” interpretations

Robust design, Short proofs, Small models

- Key to success of reductionist science in study of “simple systems”
- With largely different methods, also key to “complex technology” success stories
  - Internet, computer, VLSI
  - Aerospace, land, and water vehicles
  - Optimization-based scheduling, manufacturing, supply chain management, etc
  - Etc, etc…
- What are the essential issues and challenges?

	Small	Large
Robust/short	Simplicity	Organization
Fragile/long	Emergence	Irreducibility

Goal

Verifiable robustness and evolvability despite complex systems with uncertain components in hostile environments.

- Doesn't reductionist science already do this?
- Somewhat, but without ***reversibility*** and ***scalability***
- ***Reversibility***: Must provide systematic inference about the full complex system, not just its components
- ***Scalability***: To large, highly organized systems, controlled far from equilibrium, with uncertain components and environments

To pursue the hope

This is a parsimonious and coherent ontology for organized complexity.

There are many “success stories” but they are fragmented.

- Hard limits
- Small models
- Short proofs
- Robustness/fragility

- Architecture

Technology Success Stories

- Crucial role of software/theory infrastructure
  - Internet, computer, VLSI
  - Aerospace, land, and water vehicles
  - Optimization-based scheduling, manufacturing, supply chain, etc
- Small models
  - Multiple scale/resolution/abstraction models
  - Robustness analysis for modeling errors
  - Restrict design space to facilitate computation
- Short proofs
  - Simulation gives "short proof" of failure
  - Simulation cannot verify "correctness" ($P \neq NP \neq coNP$)
  - Increasing use of formal verification and analysis

Encouraging research progress

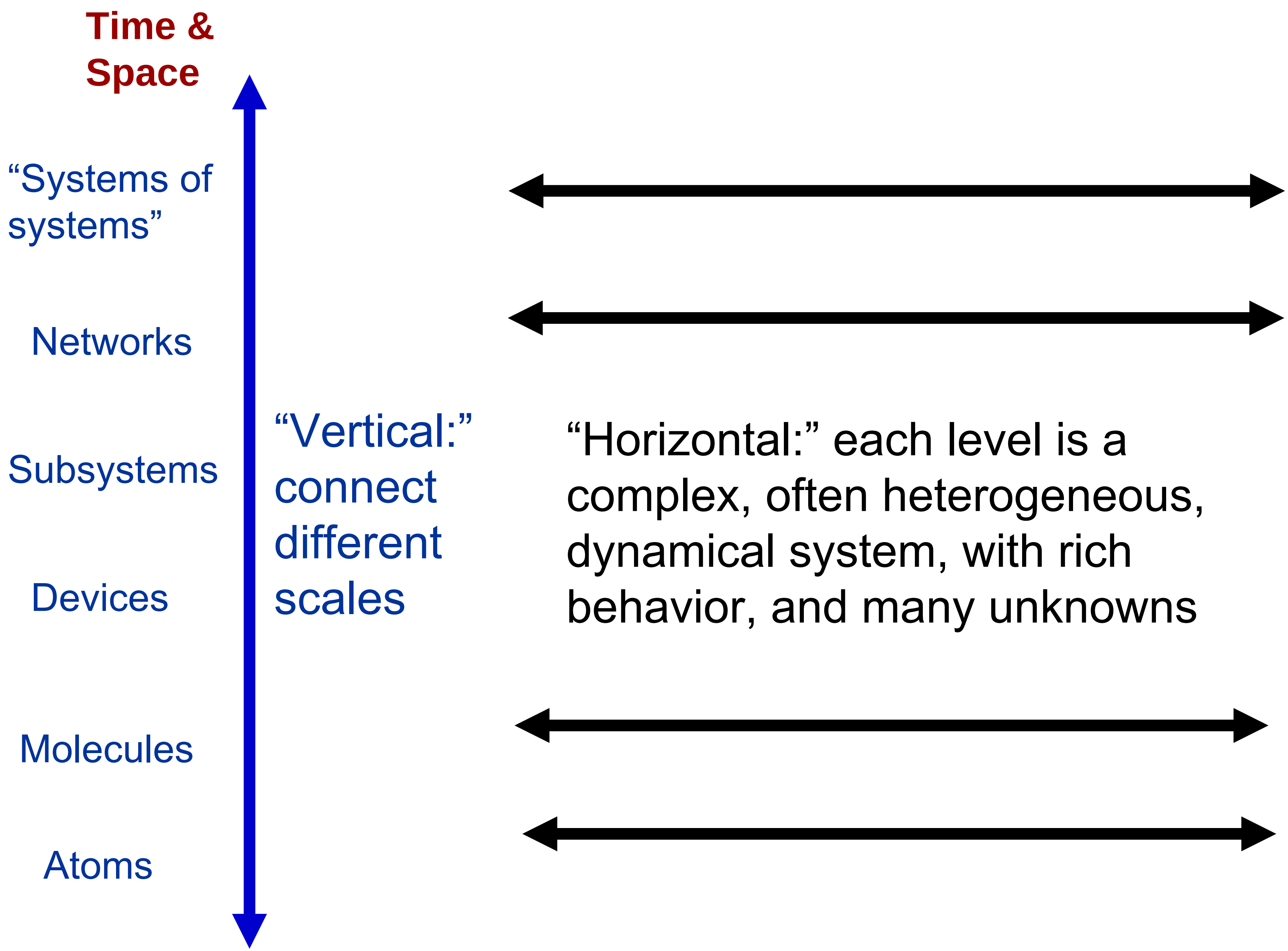
- Small models
  - System identification, machine learning
  - Model reduction with error bounds
  - More systematic multi-scale modeling
  - Scalable models of networks of interacting components (Internet, flocking, coupled oscillators,…) with proofs, not merely simulations/conjectures
- Short proofs
  - Expanded role of convex optimization and duality
  - Model checking, SAT solvers
  - SOS and P-satz certificates
  - Automated theorem proving
  - Performance/robustness of distributed/layered systems

Encouraging research progress

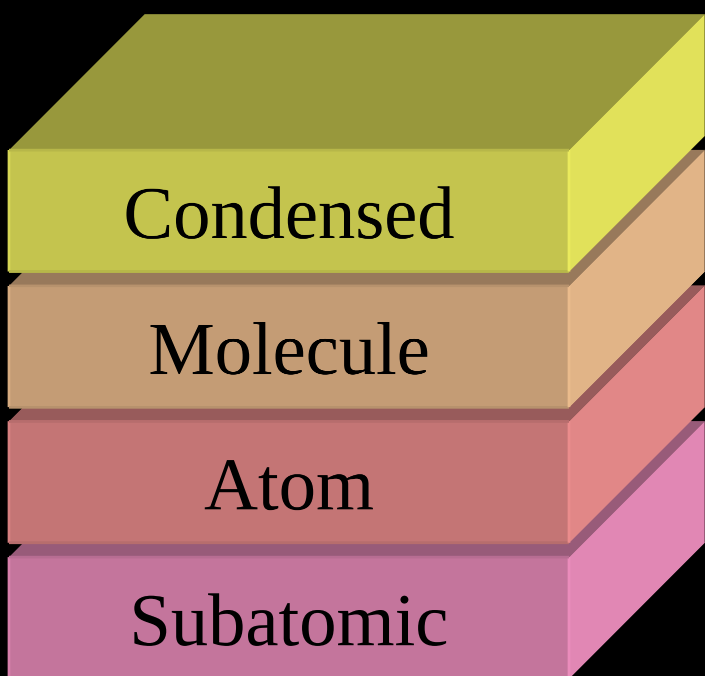
- Hard limits: Some pairwise unifications
  - Integrated Bode-Shannon theory
  - Control theoretic nonequilibrium statistical mechanics
  - “Complexity implies fragility” potentially unifies complexity theory (P=NP?, (un)decidability) with numerical analysis (condition number)

Multiscale physics and models

- ***Emergent***: Focus on most likely (and ignore rare) configurations, e.g. equilibrium statistical mechanics, ensembles, coarse-graining, renormalization
- ***Organized***: Keep only rare (but efficient, robust, structured, evolvable, etc) configurations
- Completely ***opposite*** in objectives and methods
- To build/evolve systems that push up against hard limits requires highly optimized protocols and modules
- To build/evolve systems that are robust and evolvable requires ***architecture***


Time & Space
“Systems of systems”
Networks
Subsystems
Devices
Molecules
Atoms
“Vertical:” connect different scales
“Horizontal:” each level is a complex, often heterogeneous, dynamical system, with rich behavior, and many unknowns

Traditional Multiscale physics



Emergence

- Chaos, fractals
- Power laws
- Critical phase transitions
- Self-similarity
- Universality
- Pattern formation
- Edge-of-chaos
- Order for free
- Self-organized criticality
- Scale-free networks

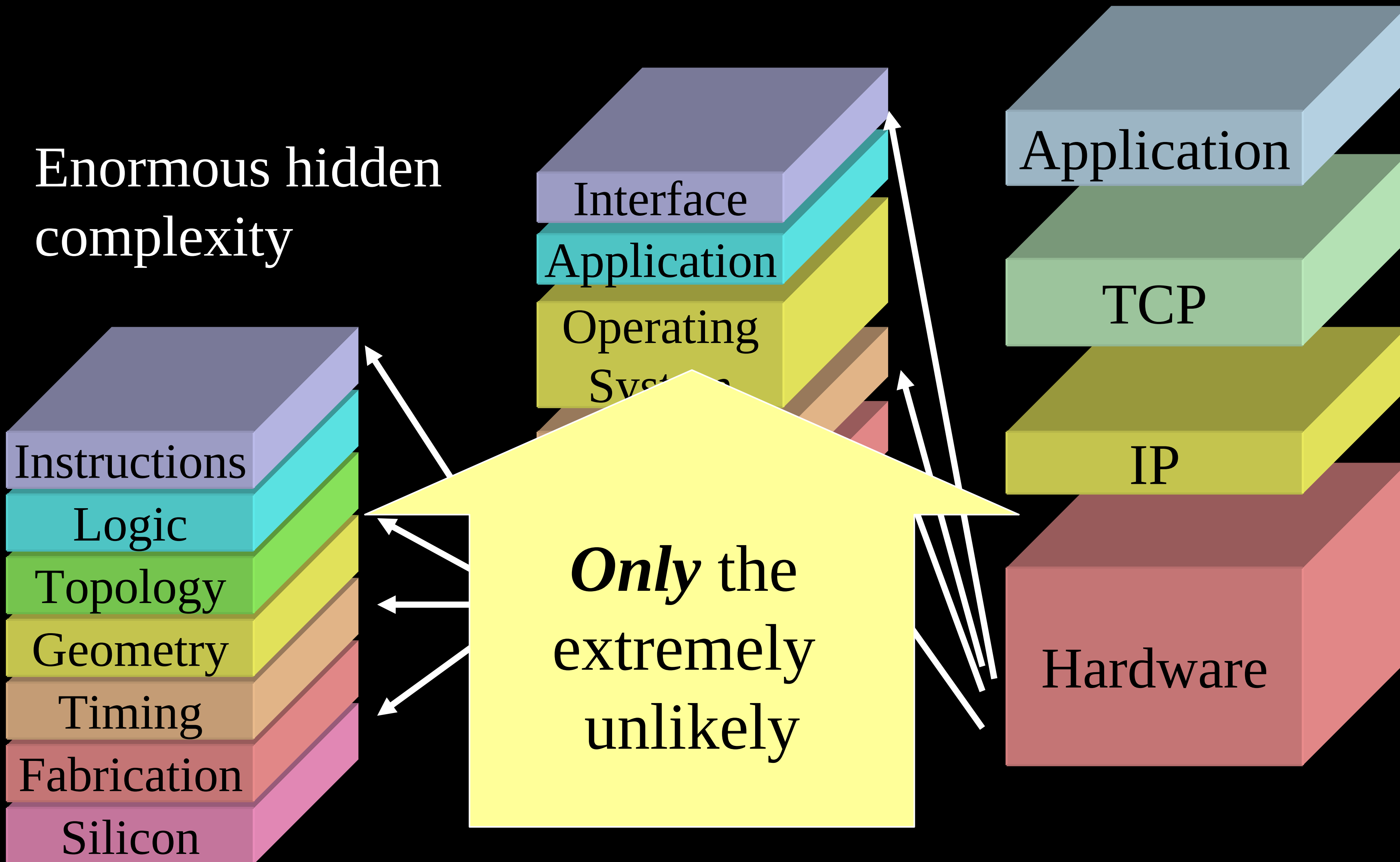
Discard the extremely unlikely

Models:

- Cellular automata
- Boolean networks
- Lattices
- Spin glasses
- Random graphs

Organized multiscale technology: e.g., the Internet

Enormous hidden complexity



Time & Space

Ecosystems

Cells

Networks

Genomes

Molecules

Atoms

Only the extremely unlikely

This demands new ways of describing multiscale complexity

“Architecture” is a central challenge

- “*The bacterial cell and the Internet have*
  - *architectures*
  - *that are robust and evolvable (yet fragile?)*”

- What does “architecture” mean here?
- What does it mean for an “architecture” to be robust and evolvable?
- Robust yet fragile?
- ***Design of architectures is replacing design of systems***

"Architecture" in organized complexity

- "Emergence" may have structure and (poorly defined notions like) "self-organization" but no architecture
- Architecture involves or facilitates
  - System-level function (beyond components)
  - Organization and structure
  - Protocols and modules
  - Design or evolution
  - Robustness, evolvability, scalability
  - Various -ilities (many of them)
  - Perhaps aesthetics
- but is more than the sum of these

Hard limits and tradeoffs

On systems and their components

- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing/Gödel)

Assume ***different*** architectures a priori.

- Fragmented and incompatible
- Cannot be used as a basis for comparing architectures
- New unifications are encouraging

Defining “Architecture”

- The elements of structure and organization that are most universal, high-level, persistent
- Must facilitate system level functionality
- And robustness/evolvabality to uncertainty and change in components, function, and environment
- Architectures can be designed or evolve, but when possible should be planned
- Usually involves specification of protocols (rules of interaction) rather than modules

“Architecture” examples

- There are universal architectures that are ubiquitous in complex technological and biological networks
- Examples include
  - Bowties for flows of materials, energy, redox, information, etc (stoichiometry)
  - Hourglasses for layering and distribution of regulation and control (fluxes, kinetics, dynamics)
- Nascent theory confirms (reverse engineers) success stories but has (so far) limited forward engineering applications (FAST TCP/AQM)

Bowties and hourglasses

- Bowties have large fan-in of diverse inputs with thin knots of universal carriers interfacing large fan-out of outputs.
- Example of carriers include:
  - Packets in the Internet
  - Lego snap
  - Money in markets and economics
  - Carriers and precursors in core metabolism
  - Histidine kinase/Aspartyl phospho-accepter in signal transduction (GPCRs and NKkB in mammals)
  - Transcription and translation in protein synthesis
- Hourglasses organize layered control architectures
  - TCP/IP in the Internet
  - Control of protein expression and protein degradation

The basis of rigor ***redux***

- Complex systems create unique challenges in creating both theoretical and experimental rigor, ***particularly with regard to architecture***:
  - Scalability to large systems
  - Robustness to component and environment uncertainty
  - Evolvability to unanticipated changes
- For example, we must explicitly mix theory, simulation, ***including hardware and human in the loop,*** and experiments in new and novel ways to investigate ***architecture***
- Huge issue needing careful thought, not enough said here (sorry)

“Complexity implies fragility?”

	Small	Large
Robust/short	Simplicity	Organization
Fragile/long	Emergence	Irreducibility

- Robustness/fragility and short/long are deeply connected
- A central, important conjecture is long proof complexity implies high problem fragility (equivalently, robust features have short proofs)
- There is overwhelming evidence and many special cases, but no complete theory
- Important implication: Robustness and verification of complexity systems are compatible design objectives

	Small models	Large models
Robust/ Short proofs	Simplicity	Organization
Fragile/ Long proofs	Emergence	Irreducibility

Organized complexity summary

- Complex systems are robust yet fragile, with unavoidable constraints and tradeoffs
- High proof complexity implies problem fragility
- Thus robustness and its verifiability are compatible design objectives
- Potentially good news for the study of all forms of organized complexity
- Needs “new math and technology” not “new science”
- Encouraging beginnings but the math is not yet readily accessible (making progress on both theory and education)